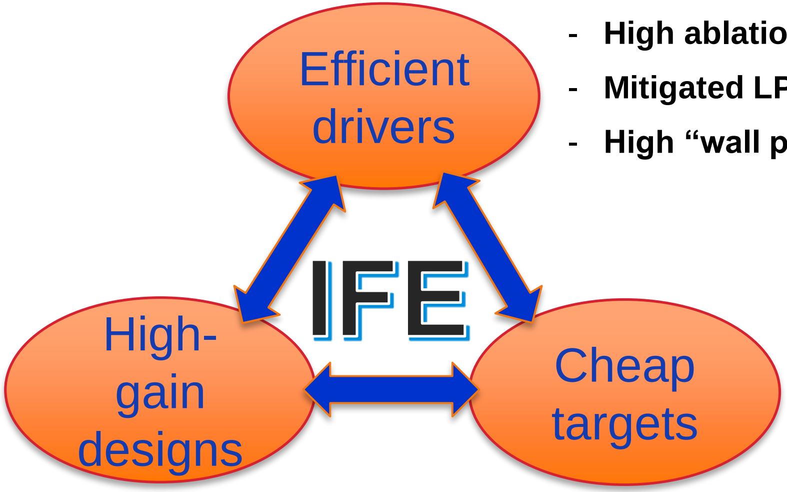
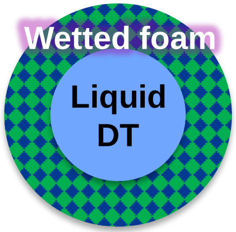
Inertial Fusion Energy Target Designs with Advanced Laser Technologies

IFE requirements (not unique!)

- **High ablation pressure**
- **Mitigated LPI**
- **High "wall plug" efficiency ($\eta > 10\%$)**



- $\eta G > 10$
- $G > 100$



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IFE Science & Technology
Community Strategic Planning Workshop
22–24 February 2022

In the hot-spot ignition approach, the hot spot initiates a burn wave into the main fuel

Hot-spot ignition approach

Compared to the current ICF implosions, the high-gain/IFE designs operate in somewhat different regions in the implosion parameter space

Current implosions

- Maximize shell kinetic E_{k} and hot-spot E_{hs} energy
- Maximize implosion velocity ($v_{\mathrm{imp}} > 4 \times 10^7$ cm/s)
- Fuel adiabat must be above a threshold value set by implosion stability
  - Penalty on convergence and ρR

High-gain designs

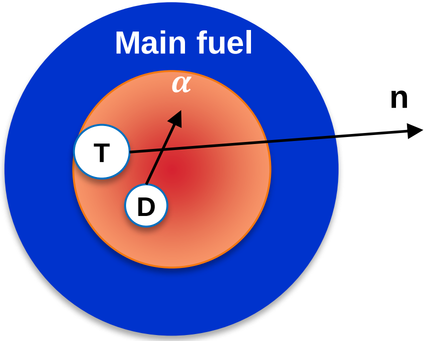
- Fuel mass is maximized
- Reduced implosion velocity ($v_{\mathrm{imp}} < 3 \times 10^7$ cm/s)
- Fuel must be kept close to Fermi degeneracy
  - Maximize convergence and ρR

How to bridge the gap?

By increasing the drive pressure! IFE will require new drivers.

The drive pressure is key to the success of IFE

- Let's review IFE fundamentals



- **Neutron yield:** $Y_{\mathrm{n}} = M_{\mathrm{burn}} \epsilon_{\mathrm{DT}}, \quad \epsilon_{\mathrm{DT}} = 2.75 \times 10^{11} \mathrm{J/g}$

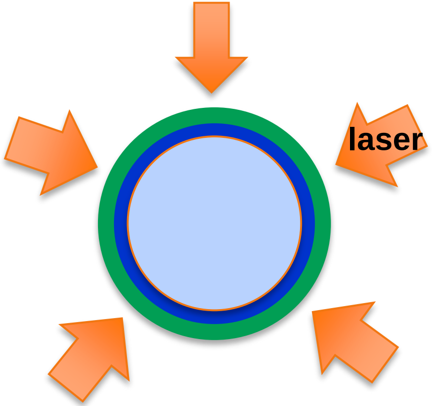
$$M_{\mathrm{burn}} = 3.7\ \mu\mathrm{g}\ \text{for}\ Y_{\mathrm{n}} = 1\ \mathrm{MJ}$$

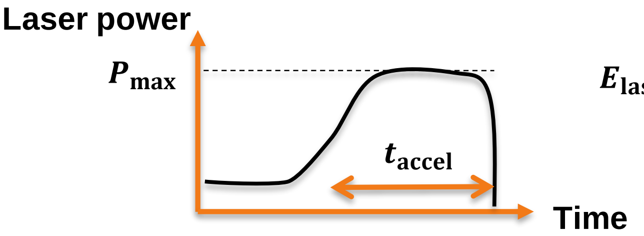
- **If we want to get Y_{n} =100 MJ: $M_{\mathrm{burn}} = 0.37$ mg**
- **Burn fraction $f_{\mathrm{burn}} \sim 1/4$: $M_{\mathrm{DT}} = 1.5$ mg**
- **We want to accelerate this mass to $v_{\mathrm{imp}} = 3 \times 10^{7}$ cm/s**
- **We will need $E_{\mathrm{k}} = (M_{\mathrm{DT}}\, v_{\mathrm{imp}}^{2})/2 = 70$ kJ**
- **Current NIF: $E_{\mathrm{k}} \sim 20$ kJ**
- **Scaled LDD OMEGA implosions to NIF energies : E_{k} =60 to 80 kJ**

Energetically, LDD makes more sense for IFE but it must remove one obstacle first!

Accelerating the required amount of fuel sets the requirement on ablation pressure

Laser irradiation provides drive pressure p_a through mass ablation





$$E_\mathrm{laser} \simeq P_\mathrm{max} t_\mathrm{accel}$$

$$M_\mathrm{DT}\frac{v_\mathrm{imp}}{t_\mathrm{accel}} \simeq 4\pi R_\mathrm{target}^2 p_\mathrm{a}$$

$$M_\mathrm{DT} \sim E_\mathrm{laser}\frac{p_\mathrm{a}}{v_\mathrm{imp}}\underbrace{\left(\frac{4\pi R^2}{P_\mathrm{max}}\right)}_{\text{Peak laser intensity } I_\mathrm{max}^{-1}}$$

$$M_\mathrm{DT} \simeq \frac{1}{5}\frac{E_\mathrm{laser}}{I_\mathrm{max}}\frac{p_\mathrm{a}}{v_\mathrm{imp}}$$

To accelerate $M_\mathrm{DT} = 1.5$ mg to $v_\mathrm{imp} = 3 \times 10^7$ cm/s at $E_\mathrm{laser} \sim 1$ MJ requires $p_\mathrm{a} > 220$ Mbar

Target gain is a simple relation between ablation pressure, implosion velocity, and peak drive intensity

$$M_{\mathrm{DT}} \simeq \frac{1}{5} \frac{E_{\mathrm{laser}}}{I_{\mathrm{max}}} \frac{p_{\mathrm{a}}}{v_{\mathrm{imp}}}$$

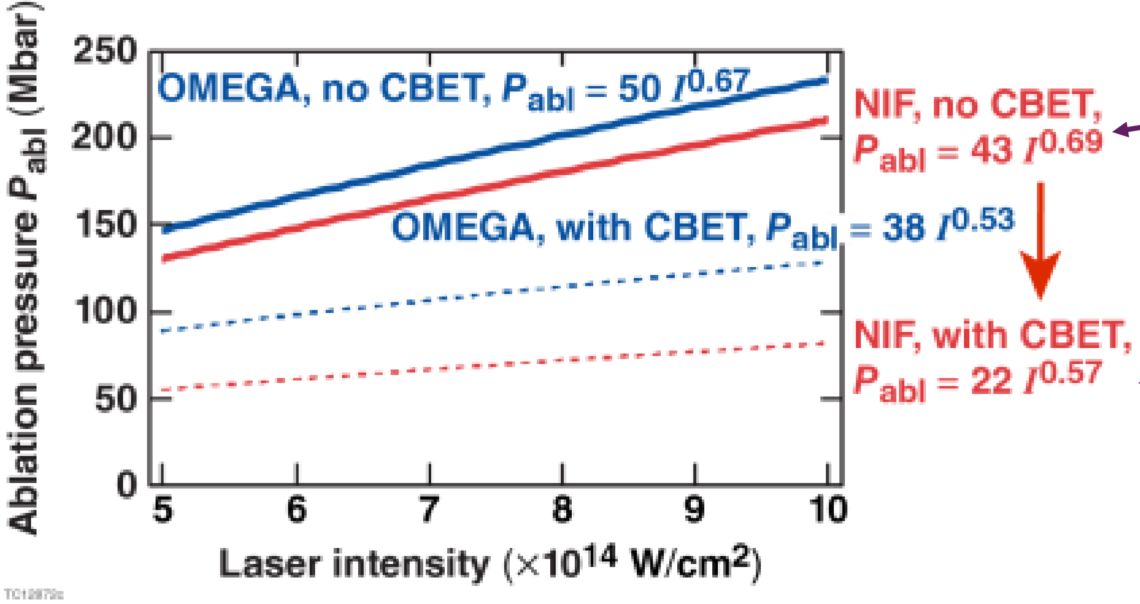
$$G = f_{\mathrm{burn}} M_{\mathrm{DT}}\, \epsilon_{\mathrm{DT}} / E_{\mathrm{L}}$$

$$\boldsymbol{G \simeq 180 \frac{f_{\mathrm{burn}}}{I_{15}} \left(\frac{p_{\mathrm{a}}}{100\ \mathrm{Mbar}}\right) \left(\frac{v_{\mathrm{imp}}}{3 \times 10^{7}\ \mathrm{cm/s}}\right)^{-1}}$$

For LDD implosions $p_{\mathrm{a}} = p_{\mathrm{a}}(I)$ depends on thermal conduction and LPI.

Ablation pressure depends on physics details

Direct Drive, $\lambda_L = 351$ nm



$$G \simeq 180 \frac{f_{burn}}{I_{15}} \left(\frac{p_a}{100\ \text{Mbar}}\right) \left(\frac{v_{imp}}{3 \times 10^7\ \text{cm/s}}\right)^{-1}$$

Bremsstrahlung absorption:

$$G \simeq 95\ I_{15}^{-0.31} \left(\frac{v_{imp}}{3 \times 10^7}\right)^{-1}$$

Bremsstrahlung + CBET losses:

$$G_{CBET} \simeq 37\ I_{15}^{-0.43} \left(\frac{v_{imp}}{3 \times 10^7}\right)^{-1}$$

$I_{15} \sim 0.1, p_a \sim 20$ Mbar

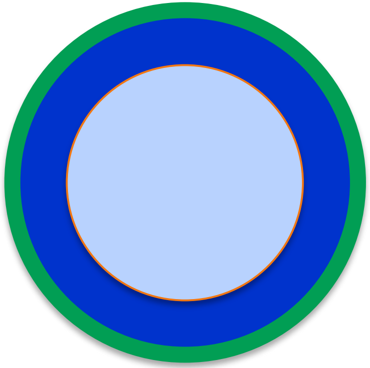
Maximizing fuel mass pushes the design to use lower drive intensities.

What's wrong with using lower drive intensities and pressures

I. Target Stability

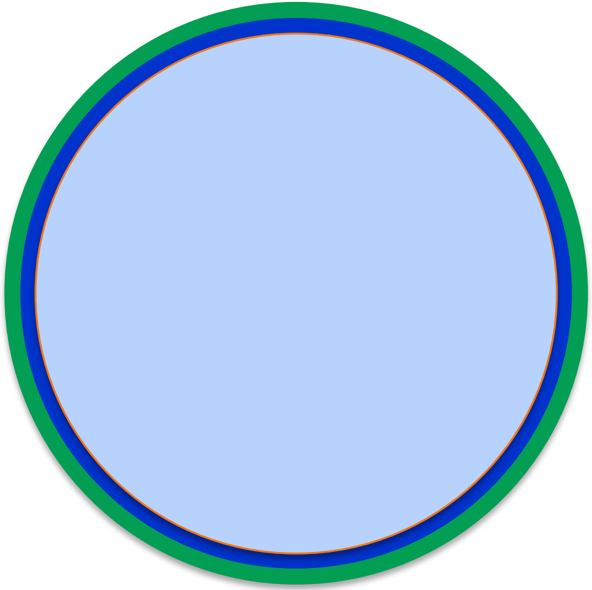
severe constraints on target quality and beam uniformity

High drive pressure



$$IFAR \sim \frac{v_{\mathrm{imp}}^2}{p_{\mathrm{a}}^{\frac{2}{5}}\alpha^{\frac{3}{5}}}$$

Low drive pressure, longer acceleration distance



To accelerate fuel mass M_{DT} with lower drive pressure requires high-aspect-ratio shells.

What's wrong with using lower drive intensities and pressures

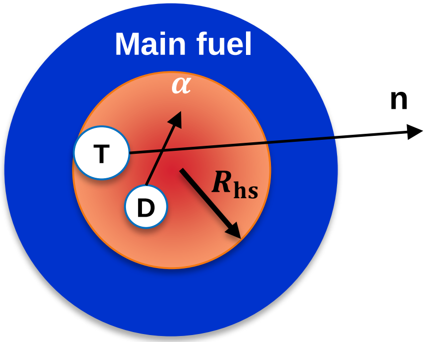
II. Creating an igniting hot spot is challenging

Lower drive pressure requires more laser energy for ignition

$$(\rho R)_{hs} T_{hs} = 0.3\,\frac{\mathrm{g}}{\mathrm{cm}^2} \times 5\ \mathrm{keV} \rightarrow$$

$$P_{hs} R_{hs} > 1\ \mathrm{Gbar} \times \mathrm{cm},\ T_i > 4.5\ \mathrm{keV}$$

$$E_{hs} > 16\ \mathrm{kJ} \left(\frac{R_{hs}}{50\ \mu\mathrm{m}}\right)^2$$



- Shell must provide efficient confinement to maximize hot-spot pressure
  - Maximum hot-spot convergence must be reached before shell starts to disassemble

If the shell's dynamic pressure ($\rho_{\text{shell}} v_{\text{imp}}^2$) is too low, the shell cannot support high hot-spot pressures ($p_{\text{hs}} \not\propto v_{\text{imp}}^3$)

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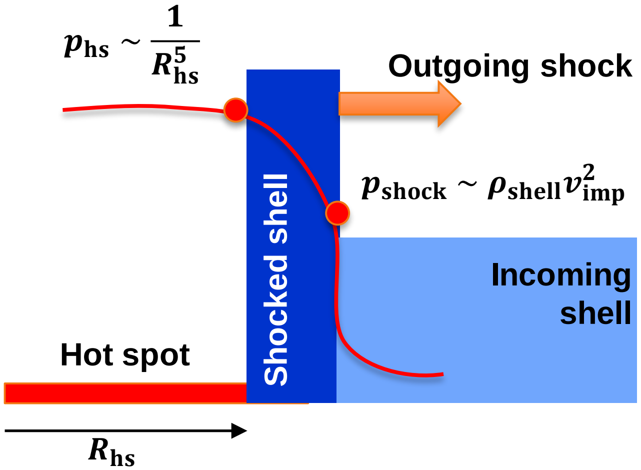
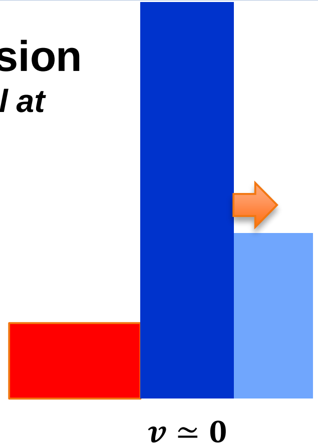


The shocked shell is decelerated by pressure gradient

$$\frac{p_{\text{hs}} - p_{\text{shock}}}{\Delta}$$

Efficient compression

Shock is inside the shell at peak compression

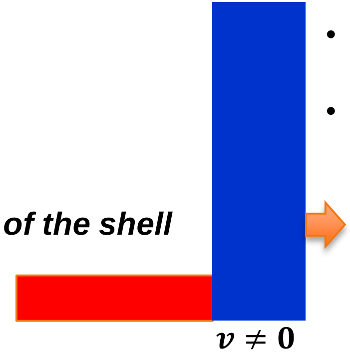


- Maximum hot-spot pressure for given implosion parameters (v_{imp}, α)

$$p_{\text{hs}} \sim \frac{p_a^{\frac{1}{3}} v_{\text{imp}}^3}{\alpha}$$

Inefficient compression

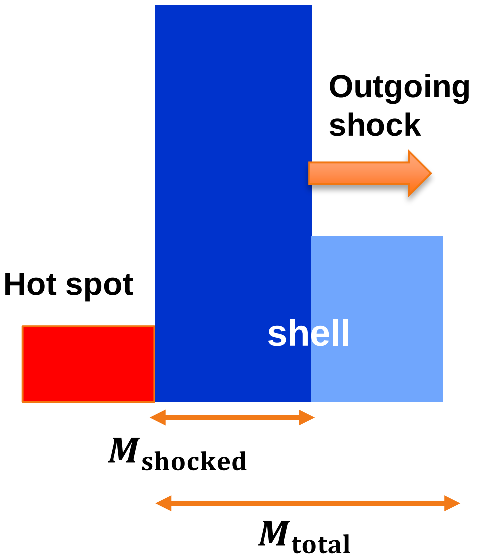
Shock breaks out of the shell before stagnation



- Shell starts to disassemble from outside
- Hot-spot convergence and pressure are limited by shell mass

$$p_{\text{hs}} < \frac{p_a^{\frac{1}{3}} v_{\text{imp}}^3}{\alpha}$$

Maximum hot-spot convergence must be reached before the outgoing shock breaks out of the shell



Efficient compression:

Shock inside the shell at peak compression:

$$M_{\text{shocked}} < M_{total}$$

$$v_{\text{imp}} < 2.6 \times 10^{7}\,\frac{\text{cm}}{\text{s}}\,\alpha^{0.3}\left(\frac{p_{\text{a}}}{100\ \text{Mbar}}\right)^{0.65}$$

Ablation pressure sets the limit on the maximum implosion velocity for an efficient piston.

What's wrong with using lower drive intensities and pressures

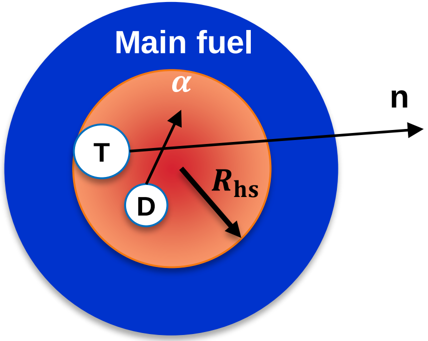
II. Creating igniting hot spot is challenging

Lower drive pressure requires ***MUCH*** *more laser energy for ignition*

$$(\rho R)_{hs} T_{hs} = 0.3 \frac{g}{cm^2} \times 5 \text{ keV} \rightarrow$$

$$\boxed{P_{hs} R_{hs} > 1 \text{ Gbar} \times \text{cm}, \; T_i > 4.5 \text{ keV}}$$

$$\boxed{E_{hs} > 16 \text{ kJ} \left(\frac{R_{hs}}{50\ \mu m}\right)^2}$$



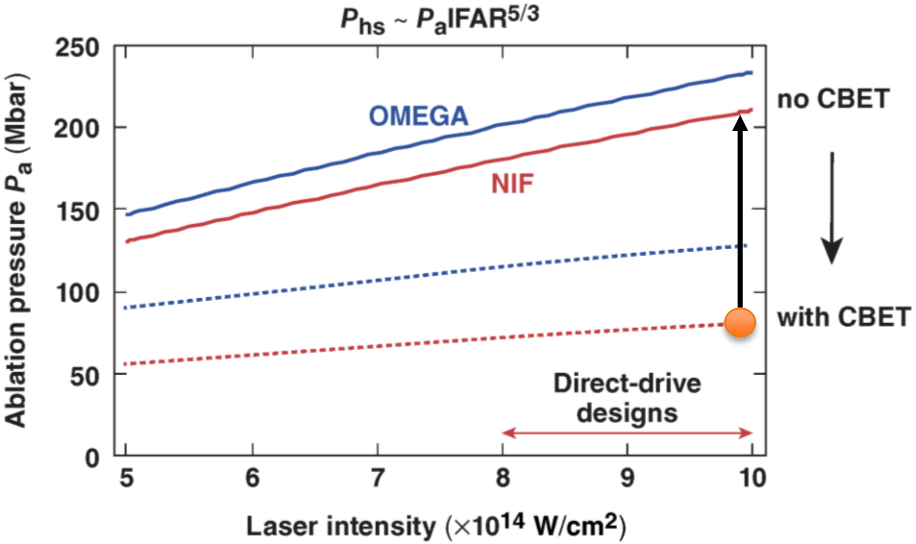
$$v_{imp} < 2.6 \times 10^7 \frac{cm}{s} \alpha^{0.3} \left(\frac{p_a}{100 \text{ Mbar}}\right)^{0.65}$$

$$\boxed{E_k(\text{kJ}) > 156 \left(\frac{p_a}{100 \text{ Mbar}}\right)^{-5}}$$

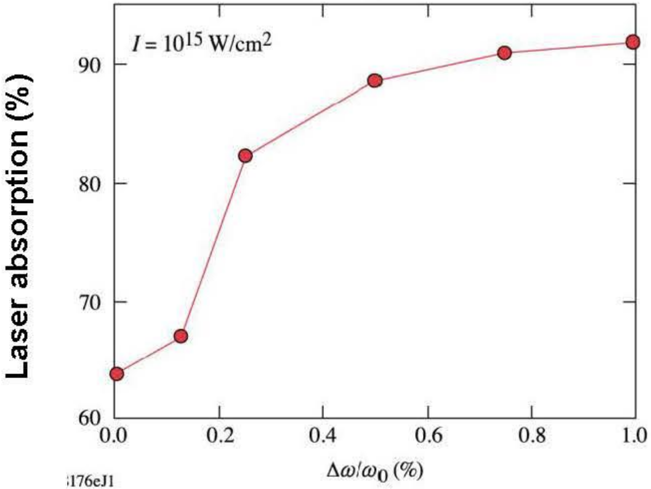
Current LID: $P_a \simeq 150$ Mbar $\rightarrow E_k > 20$ kJ **– right at the edge**

Required energy increases rapidly with reduced drive pressure $P_a = 100$ Mbar $\rightarrow E_k > 156$ kJ

The path forward for laser-driven IFE is to reduce LPI losses and maximize ablation pressure with broadband lasers



Crossed-beam energy transfer
(Increased drive pressure)



- Broadband illumination also mitigates imprint

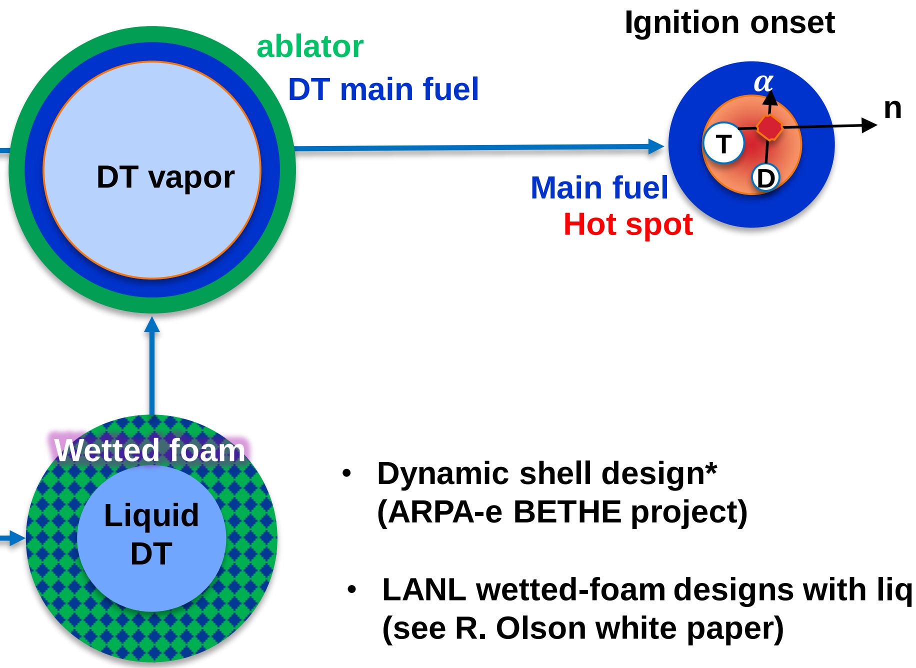
A shorter-wavelength ArF driver also provides improved ablation pressures (see talk by S. Obenschain and whitepapers from NRL)

Targets for IFE must be cheap!

Hot-spot ICF approach

Conventional hot-spot ICF approach

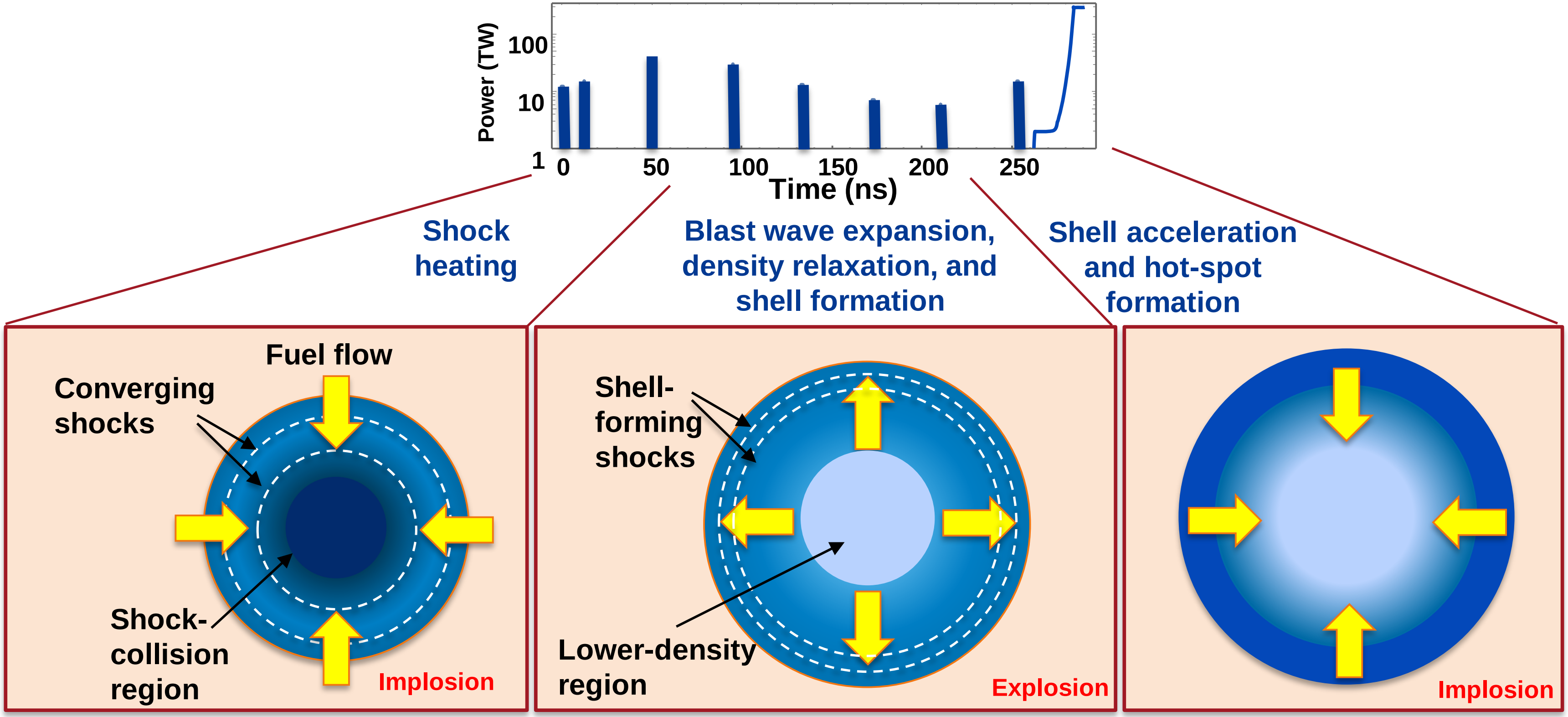
Possibly a better path for IFE: start with liquid DT ball



- Dynamic shell design* (ARPA-e BETHE project)
- LANL wetted-foam designs with liquid DT layers (see R. Olson white paper)

* Goncharov *et al.*, PRL 125, 065001 (2020).

The dynamic shell design evolves through three stages



Priority list for laser-drive IFE

1) Demonstrate the engine

- Broadband glass lasers (Jon Zuegel's talk)
- Excimer lasers, ArF (Steve Obenschain)

Recommendation:

- *A single-beam prototype should test feasibility of laser meeting efficiency, high rep-rate requirements*
- *A test compression facility must provide data on improved drive pressures and reduced LPI;*

  LPI is multibeam phenomena so single-beam test beds will not deliver the required validation

2) Demonstrate feasibility of cheap targets

Recommendations:

- *Wetted-foam ablators must be validated on current facilities (OMEGA)*
- *Several stages of advanced designs (i.e., dynamic shell concept) can be tested on current lasers (proof-of-principle experiments)*

BACKUP slides

Proof-of-principle experiments are scheduled on OMEGA on 16 August 2022 as part of the LBS program

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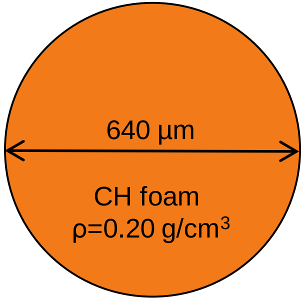
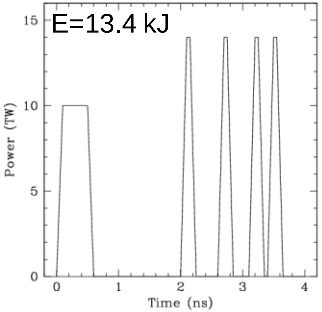
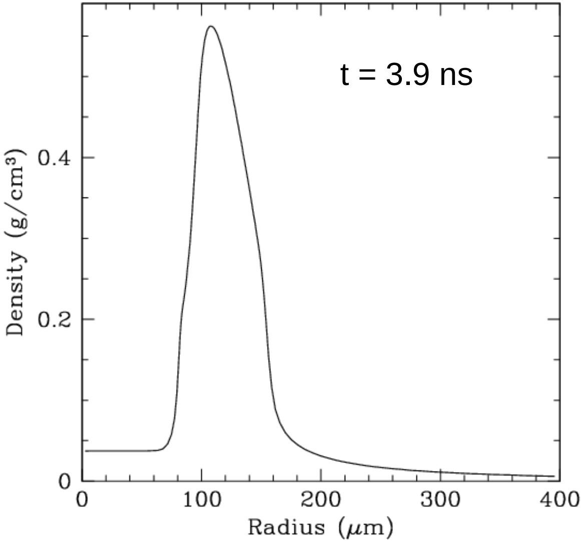
Target



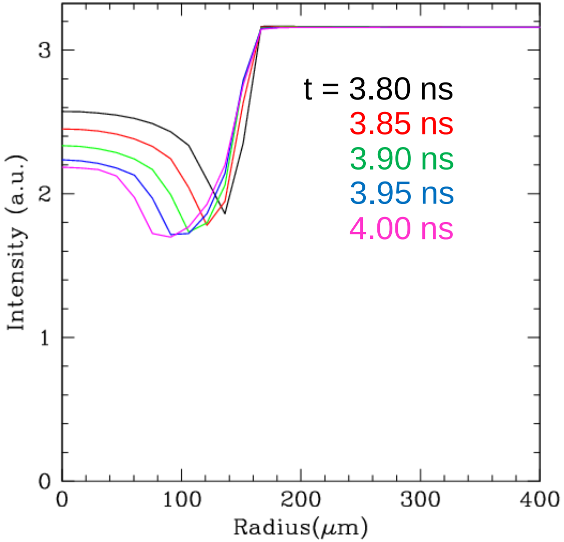
Laser pulse using SG5-650



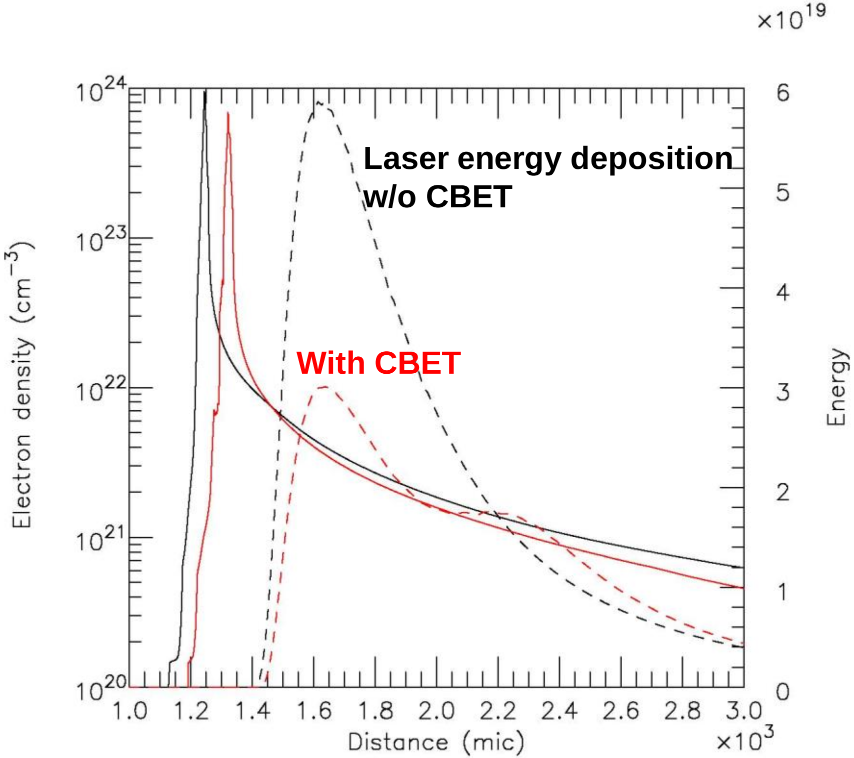
Density

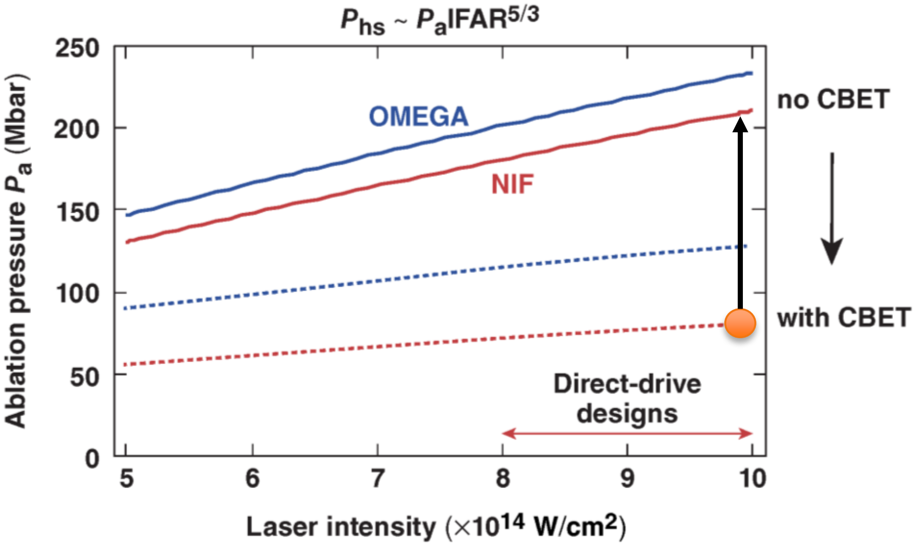


Backlighting at 1.85 keV (400 eV source)



LPI coupling losses shift the laser deposition region further out into plasma corona





Further improvement in ablation pressure can be achieved through beam zooming; shorter-wavelength driver (ArF) is also helpful

Pulse shape consists of set of pickets and the main drive pulse